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TITLE: Mine Detection in Dry Soils Using Radar  
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ABSTRACT: The detection of mines and subsurface ordnance continues to present a challenging problem for both the Army and the U.S. Marine Corps. An initiative was launched by the Army's Topographic Engineering Center (TEC) to determine the feasibility of using penetrating radars to detect subsurface objects in very dry soils. A test site was selected at Twentynine Palms, CA, and soil samples were collected and analyzed. The soils were very dry, containing on average less than 2 percent moisture, and consist mainly of fine sand with some gravel. An analysis of soils collected in The Middle East showed they were sufficiently comparable for the demonstration.

A minefield test site was constructed reflecting known doctrine and combat engineering practices. Metallic and nonmetallic mines were emplaced on the surface and at varying depths. Corner reflectors were placed around the test site, both on the surface as well as underground. Overflights were conducted utilizing X-, C- and L-band radars.

Analysis of the data revealed that direct detection of mines, even in very dry soils, is difficult. Metallic surface mines are readily detectable, but nonmetallic surface mines are less readily detectable. There is as yet no evidence of signals from subsurface mines; further processing may yield such signals. Algorithms have been developed that permit the detection and isolation of linear patterns associated with minefields. Radar signals of surface conditions in mined areas (e.g. the presence of disturbed soil surfaces or surface features associated with minelaying activities) appear to present more reliable evidence of minefield locations. There are several possible sources of signals from disturbed soil; experiments are underway to determine the source(s) of the signals.

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Mine Detection in Dry Soils Using Radar (U)

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Introduction

This project resulted from two independent developments. First, minefields could be anticipated as a major part of the defense system in any military action in the Middle East. Second, previous work showed that subsurface features and former waterways were detectable by spaceborne radars in arid soils.<sup>1,2,3</sup> Other investigators<sup>4,5,6,7</sup> provided similar supporting evidence of ground-penetrating radar capabilities, particularly in arid regions. Although a number of previous studies have been conducted to remotely detect mines, none of these attempted to exploit the penetrating capabilities of long-wavelength radar for this application in arid soils. Based on these developments, an effort was launched to demonstrate the feasibility of detecting minefields in dry soils using L-band imaging synthetic aperture radar (SAR). Buried mines were not detected under the conditions of the experiment, but a surprising result was a strong signal of disturbed soil obtained under some conditions. These findings provide a number of opportunities warranting further research.

Background

The project plan developed by the Army's Topographic Engineering Center (TEC) involved: (1) locating a site that contained dry, sandy soils, (2) constructing a minefield representative of a typical threat, (3) imaging the site with an airborne radar system, and (4) assessing the usefulness of the information to Army image analysts and others.

The U.S. Marine Corps Air Ground Combat Center (MCAGCC) at Twentynine Palms, California was selected for the test site because it offered several advantages. These included: (1) dry soils, (2) a secluded test site that could be protected, (3) few problems with respect to air traffic control, since MCAGCC is off-limits to commercial aircraft, and (4) Marine Corps assistance in terms of personnel and equipment to perform the test.

The site selected is near Gypsum Ridge (coordinates 78°01'; 34°20'30"N,

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116°9'W). It is indistinguishable from many sites in the Middle East. Of the many variables affecting the results of radar ground-penetration studies, moisture is probably the most important. Water is an efficient absorber of microwave energy, and its presence reduces penetration. Dry soils are thus most desirable for such experiments, and soil moisture content of less than 2 percent is an acceptable upper limit (G.G. Schaber, U.S. Geological Survey, personal communication, 1991). Surface soil moisture contents between 0.33 percent and 0.50 percent for Twentynine Palms are thus acceptable.

Soil samples from the Middle East were located from various sources. It was not possible to determine soil moisture content on the samples from the Middle East, because they were not collected under controlled conditions. However, citations in the literature suggest soil moisture is significantly below 1 percent. These samples were compared to soils from Twentynine Palms with respect to particle size and were determined to be adequately similar, although the soils from the Middle East are slightly coarser grained and contain more gravel than those from Twentynine Palms.

A test plan reflecting the type of mines and minefields anticipated in Middle East scenarios was developed. Personnel at Belvoir Research, Development and Engineering Center (BRDEC) provided outstanding support in terms of technical advice, and in providing sources and details regarding recommended test mines. The metallic mine chosen was the M-12 training mine. Nonmetallic test items were fabricated with the same dielectric constant as known threat nonmetallic mines (Figure 1). Both types of mines were approximately 0.3m in diameter.

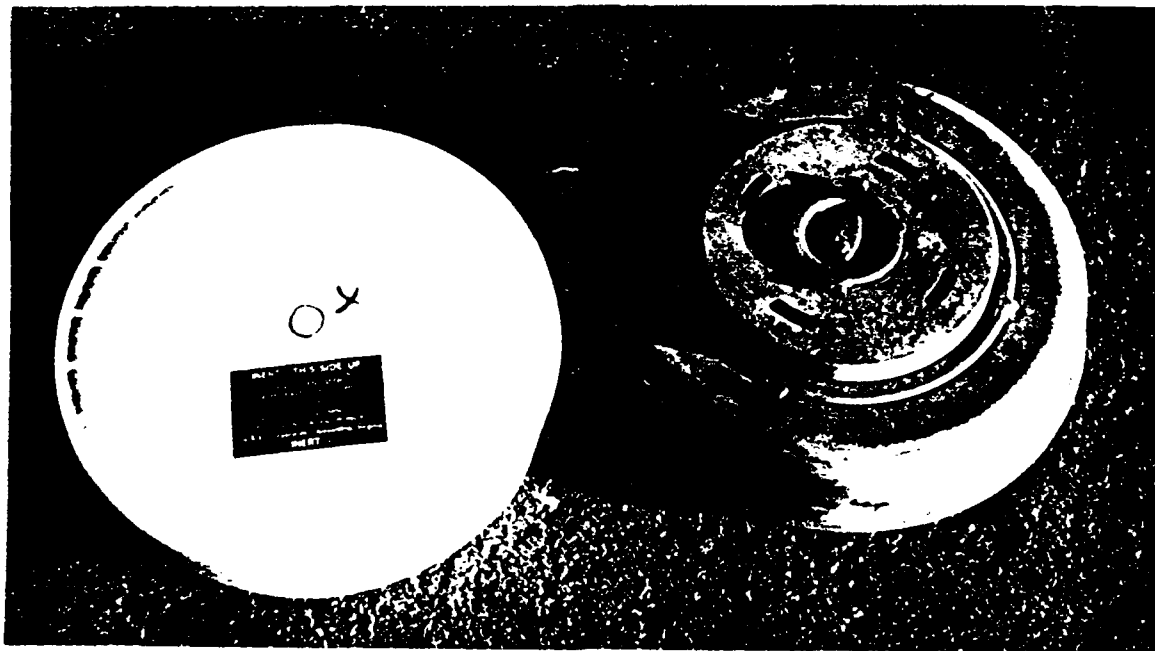


Figure 1 Nonmetallic and Metallic Mines

The test plan was driven primarily by the desire to locate subsurface metallic mines. Nonmetallic mines are also recognized as a potential threat, but the close dielectric constants of such mines and the surrounding sand (approximately 2.5) do not offer much encouragement for detection. They were included in the test plan shown in Figure 2, however, for experimental purposes. Surface mines, both metallic and nonmetallic, were included for several reasons. Although surface mines might not be expected in deliberate minefields, they could be encountered in hasty minefields, or in instances where soil covering shallow mines had been removed by wind, exposing the mines. In addition, they provided a specific indication of the location of the buried mines in the test plan layout. Finally, data were sought on the difference in signals between surface mines and those buried at shallow depths.

A Navy P-3 aircraft carrying X-, C-, and L-band, synthetic aperture radar (SAR) using several polarizations operated by the Naval Air Warfare Center in Warminster, Pennsylvania was used in the demonstration. An airborne radar platform carrying long-wavelength radar was desired because of the relation between radar wavelength and penetration: greater penetration is expected as the wavelength increases, as long as the moisture content is low. Table 1 shows the parameters of this airborne radar system. The resolution shown was considered adequate, given that the mines were spaced at 5m intervals.

Table 1: P-3/SAR Characteristics

**System Parameters:**

Bandwidth	60 MHz	120 MHz
Impulse Response Width	3 m	1.5 m

**Antenna Parameters:**

	X	C	L
Wavelength (cm)	3.20	5.70	24.00
Frequency (GHz)	9.35	5.30	1.25

**Resolution:**

Cell size (m)			
range	1.80	1.80	1.80
azimuth	0.80	0.80	1.10

## Phase I

The test site was surveyed and cordoned off with stakes and tapes, and corner reflectors were placed at test site corners. The site was then overflown to obtain images at altitudes of 7,500 and 12,500 feet with X-, C-,

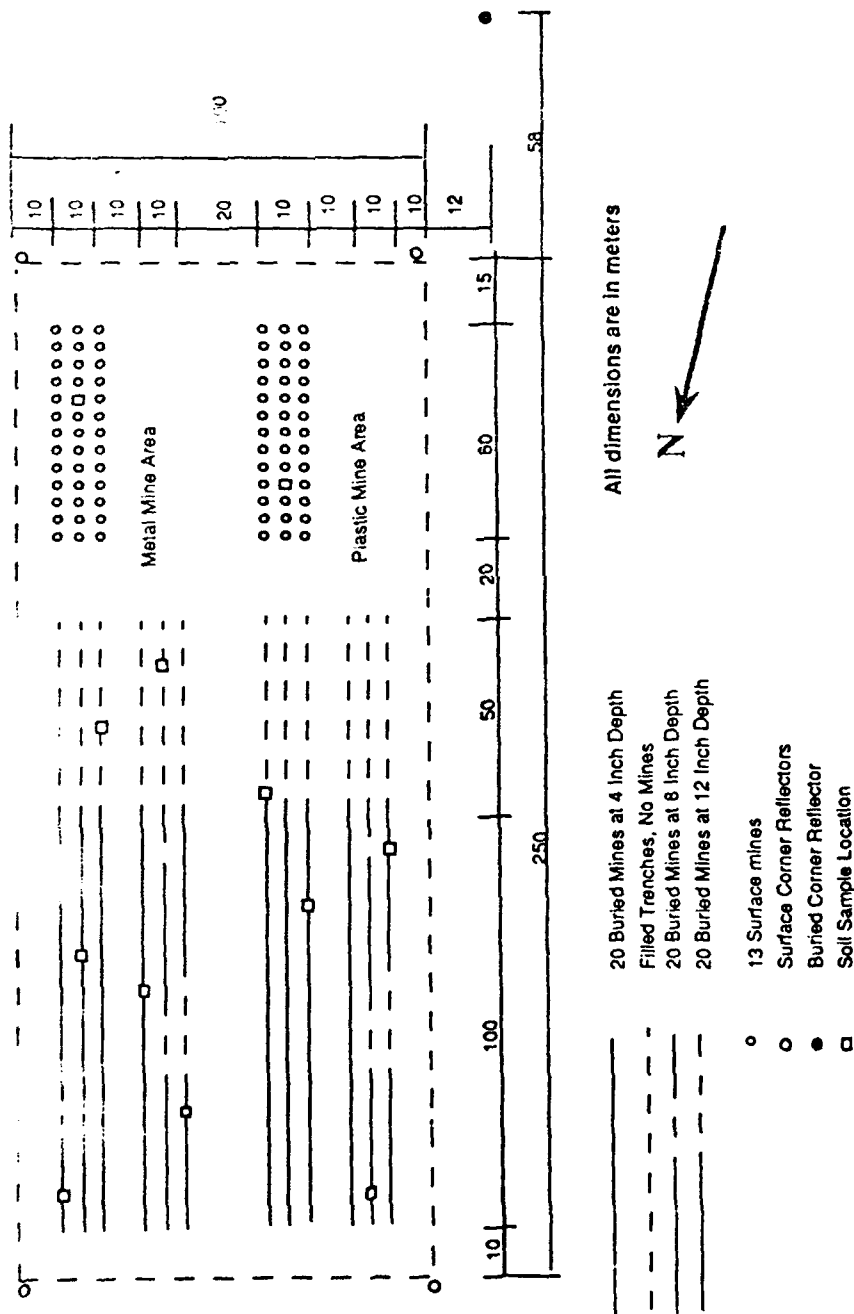


Figure 2 Test Site (Phase I)

and L-band radars. Next, the minefield was constructed using a Small Emplacement Excavator (SEE), which is a militarized backhoe, and a road grader with the blade sharply tilted to produce a v-shaped trench. Mines were surveyed in, with both the intervals between mines and depth being carefully measured (Figure 3). The southern 50 meters of each trench was deliberately left without mines. The first four trenches (on the northeast corner of the site) were dug by the SEE; the remaining trenches were dug by the grader. During site construction, soil samples were gathered from various locations and depths within the trenches.<sup>8</sup> Soil pits were also dug to permit further soil characterization, and surface roughness determinations were made.<sup>9</sup> When all mines were emplaced, the trenches were back-filled. Both the SEE and manual labor were used to backfill the three most easterly trenches. The grader was used to backfill the remaining trenches, covering most of the surface surrounding the trenches with the loose soil removed from the trenches. The area containing surface mines was not significantly disturbed. As soon as the minefield was completed, the site was imaged again. Finally, the minefield was dismantled. The mines were readily located (reflecting the excellent surveying work performed by the Marine Corps personnel) and were removed from the site. The site was then imaged a third time with the radar systems. The imaging overflights were conducted in a three-day period.



Figure 3 Mine Emplacement

## Phase II

A month after the first site was dismantled, a second, adjacent site was constructed to obtain additional imagery. The design of this site was the same as the Phase I site, with minor changes (see Figure 4): This site was to be retained for an extended period of time (it is still in existence), and therefore was bordered with barbed wire, with an outer border of concertina wire. Again, a road grader was used to dig the trenches. Care was taken during minelaying operations to confine the area of disturbed soil as much as possible to the trenches in which the mines were laid, in order to simulate the type of disturbance likely to be caused by a minelaying plow. The Phase II site thus contains significantly less disturbed soil than the Phase I site. Soil samples were taken from the same relative locations as in the Phase I site (e.g., samples were taken from both sites at row three, mine 4, etc.). The Phase II site is slightly more moist throughout than the Phase I site (surface soil moisture ranges from 0.47 percent to 1.31 percent), but there were no statistically significant differences between the two sites.<sup>8</sup> Grain size distributions in the soils from the two sites are also comparable.<sup>8</sup>

## Radar Imagery

A total of 144 radar phase histories were obtained from overflights of the test site on five separate days. Of these, 95 were taken during Phase I, and 17 were obtained in Phase II. In addition, 32 images were taken three months after the Phase II overflight. HH, VV, HV, and VH polarizations were used in the X, C, and L radar bands. Data were taken at incidence angles of 35 degrees, 50 degrees and 70 degrees. Processing and analysis of the phase histories concentrated on the L-band images, because greater soil penetration was expected with the longer wavelength. The images were processed and analyzed using conventional techniques. New pattern-finding algorithms were also developed during the course of the work. Table 2 summarizes the findings from L-band imagery.

## Phase I Results

Unless stated otherwise, both the results described below and the discussion that follows refer to L-band radar.

**There is no evidence of buried objects in the imagery.** No buried mines or buried corner reflectors were identified by trained Army image analysts in any of the Phase I images. This is true regardless of wavelength, polarization, and incidence angle.

**A strong return was obtained in the area of disturbed soil on the test site in some of the images.** This signal is strongest with VV polarization, and at the lowest incidence angle (35 degrees) used. Figure 5 shows a strong signal on L-band images where the soil was disturbed.

**Pattern-finding algorithms have been developed that can identify/isolate**

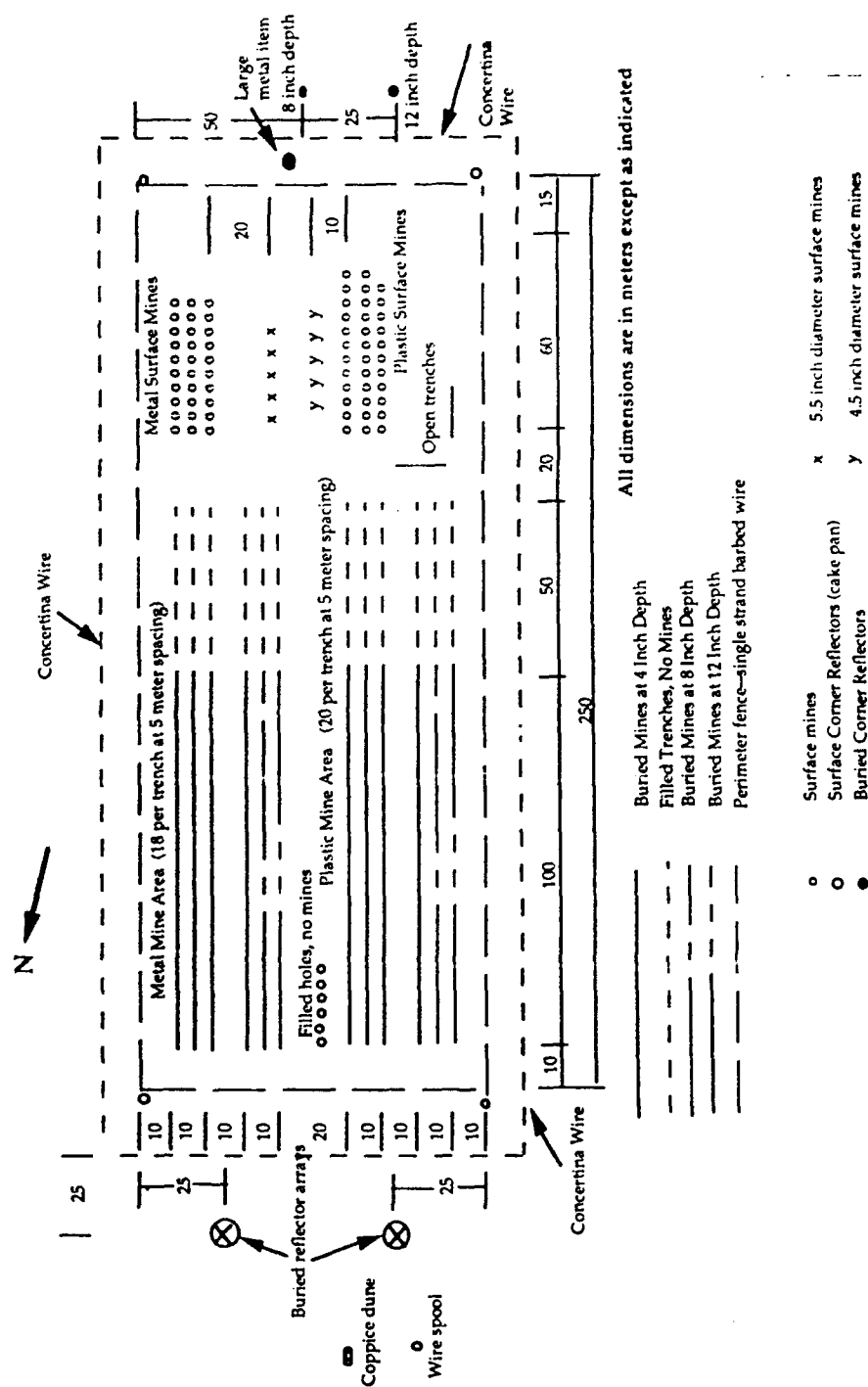


Figure 4 Test Site (Phase II)

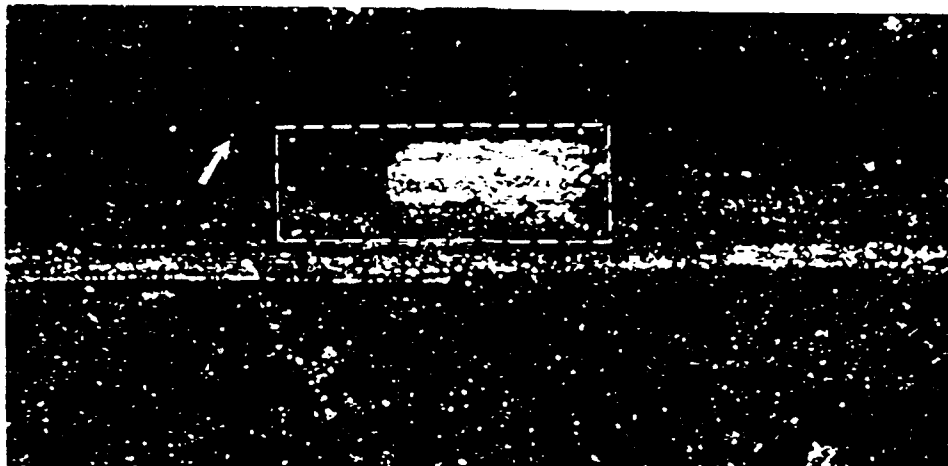


Figure 5 L-band Image Showing Disturbed Soil on Test Site, and Possible Signal from Buried Corner Reflector (arrow)

Table 2: Types of Signals

Incidence Angle	Band/Polarization			
	L <sub>HH</sub>	L <sub>HV</sub>	L <sub>VH</sub>	L <sub>VV</sub>
<b>Phase I:</b>				
35	disturbed soil no mines	disturbed soil no mines	disturbed soil no mines	disturbed soil weak mines
50	disturbed soil no mines	weak disturbed soil no mines	weak disturbed soil no mines	disturbed soil no mines
70	no disturbed soil no mines	no disturbed soil no mines	no disturbed soil no mines	disturbed soil weak mines
<b>Phase II:</b>				
35	N/A no disturbed soil mines not resolved	N/A	N/A	N/A
50	N/A	N/A	N/A	N/A
70	no disturbed soil mines not resolved	N/A	N/A	no disturbed soil no mines

linear features frequently associated with minefields and the related pattern of disturbed soils. Algorithms have been developed and applied to the linear features associated with the surface metal mines. These algorithms appear robust and may ultimately provide a mechanism to assist image analysts in automatically detecting/isolating linear features associated with minefields.

**Strong returns are given by metallic surface objects in some images.** Corner reflectors, metal stakes bordering the site, and metal surface mines are clearly visible, and are individually resolved in the C-band imagery. In L-band imagery, the metallic surface mines gave a weak return and were not individually resolved in VV polarization. The surface metal mines were not seen in cross-polarized L-band images nor in L-band images with HH polarization. Fence posts are visible in some L-band images, and on C-band images. Posts in the range direction (East-West) produced stronger images than those in the along-track direction (North-South).

**Nonmetallic surface mines are not readily detected.** None of the nonmetallic surface mines are visible in any of the L-band images. A few nonmetallic surface mines are weakly visible in C-band images.

#### Phase II Results

**Strong returns were obtained from metal posts, barbed wire, concertina wire, and surface metal mines.** In particular, a very bright return was seen from the single roll of concertina wire used to mark the outer boundary of the site. The surface metal mines were highly visible on several of the L-band images, but were not individually resolved. They were individually resolved on one X-band and one C-band image.

**There is no evidence of disturbed soil (i.e. trenches, vehicle tracks) on any of the images.** L-band imagery shows no evidence of returns that can be attributed to disturbed soil. Figure 6 shows a C-band image of the Phase II site. The barbed wire, and particularly the concertina wire, are clearly visible, but there is no signal from disturbed soil. Note that metallic surface mines are clearly resolved, as was shown in Phase I imagery as well.

**There is no evidence of buried mines, either metallic or nonmetallic.** Figure 5, however, may show a buried corner reflector. The bright returns at the four corners of the site are corner reflectors located on the surface. A fifth corner reflector is located on the surface near the upper left corner of the site. Halfway between this fifth surface reflector and the reflector at the upper left corner of the image, a corner reflector was buried. This reflector is vertically oriented. Its uppermost tip is located just below the soil surface; its corner is therefore 0.5m below the surface. There is a bright spot in this image in the correct position for a return from this buried reflector; this requires further experimental confirmation.

#### Discussion

The fact that no signals from buried mines and buried corner reflectors

were readily identified in this experiment using L-band radar indicated that the technology is not as robust as some might expect. The ground penetration achieved by the SIR-A, SEASAT, and SIR-B L-band radars occurred under very special conditions. Analysis of SIR-A images of North Africa followed by intensive field work showed that significant ground penetration occurred,<sup>1,2</sup> and as a result the potential penetrating capabilities of SEASAT were investigated in the Mojave Desert by Blom, et al., who detected subsurface dikes.<sup>3</sup> Subsequently, penetration also occurred in northern Saudi Arabia using SIR-B.<sup>7</sup> The explanation for these results compared with our own at Twentynine Palms undoubtedly lies in the complex nature of microwave ground-penetration physics. According to McCauley, et al.,<sup>1</sup> variations in radar image tone are caused by changes in radar backscatter, which is mainly determined by (1) physical properties such as slope, surface roughness, and characteristics of the soils; (2) subsurface roughness where penetration occurs to a significant degree; (3) the propagation wavelength; (4) the angle of incidence; (5) the polarization of the incident wave; (6) a complex dielectric constant, which in most instances is dominated by moisture content and density; and (7) a complex volume scattering coefficient applicable to random media. Given the complexity and number of variables involved, it is apparent that straightforward explanations for the results described above

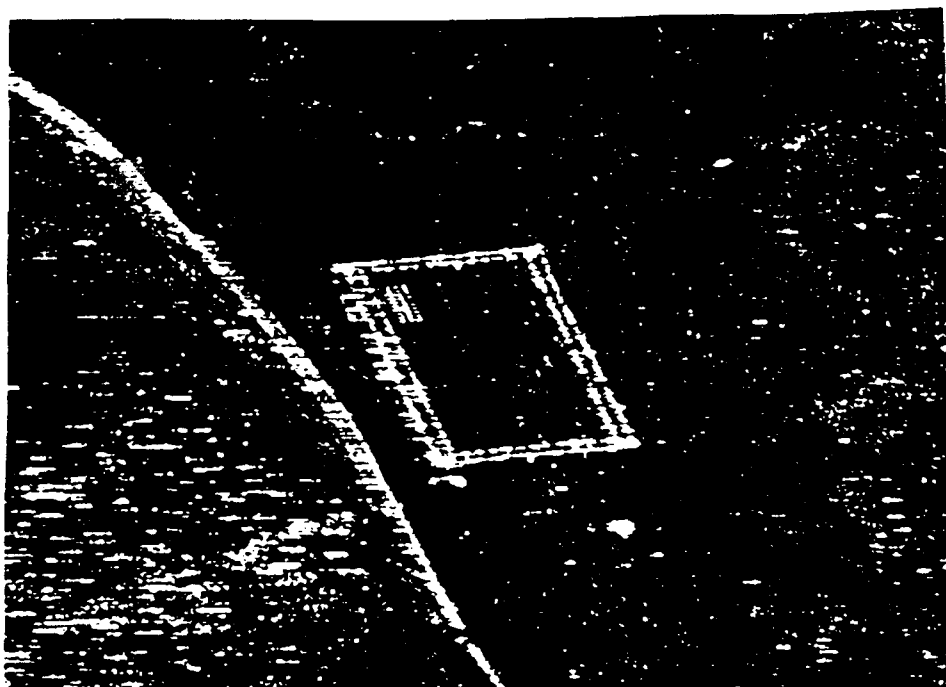


Figure 6 C-band Image Showing Barbed Wire,  
and Surface Metallic Mines

should not be expected. In addition, the objects sought in this test were metallic mines, approximately 0.3m in diameter. These are small targets when compared with the much larger terrain features in other studies using ground-penetrating radars.<sup>1,3</sup>

Surface roughness, in terms of radar return, deserves a comment. At the Phase I site at Twentynine Palms, surface variations were on the order of one-quarter to one-half wavelength (L band = 24 cm) over a distance of a few meters, and thus approached the criteria for being "radar rough". As stated above, because of the disturbed soil signals obtained in Phase I, efforts were made in Phase II to reduce the amount and area of surface roughness. No disturbed soil patterns were seen on the Phase II imagery. However, to the extent that Phase I was more representative of typical military construction activity, these results suggest that disturbed soil patterns might possibly be used as an indicator of such activity.

The effects of soil moisture warrant comment since there is general agreement that this factor may dominate all others. Many investigators (C.G. Schaber, U.S. Geological Survey, personal communication, 1991) believe that at moisture levels below approximately 2 percent, the soil is adequately dry to achieve penetration when other conditions, such as soil homogeneity, composition (to include salts and clay content), and particle size, are favorable. The effect of soil moisture reducing radar returns was demonstrated by Blom, et al.<sup>3</sup> who were unable to detect buried corner reflectors when soil moisture was in excess of 5 percent. Layering identified in soil pits at the Phase I site is most likely insignificant;<sup>9</sup> clay contents are very low and no salts (such as carbonate or gypsum) were identified; and there were no statistically significant differences in particle size with depth.<sup>8</sup> Surface soil moisture in Phase I ranged from 0.33 percent to 0.50 percent, and in Phase II, from 0.47 percent to 1.31 percent; there were no statistically significant differences in soil moisture with depth or between the two sites. These conditions meet those generally accepted as adequate for penetration to the depths of interest.

The amount and particle size of surface gravel may also have effected the results of this experiment. Blom, et al.<sup>3</sup> report that for L-band radar, surface gravel should be less than 1.5cm to prevent scattering losses; successful penetration has occurred only where sand is predominant and any gravel present is very small and scattered. Gravel in surface samples from Twentynine Palms ranged from 5.2 percent to 34.8 percent, much of which was 1.5 cm or larger in size. Subsurface gravel contents were comparable, as was particle size, so even if surface penetration occurred, scattering losses would be likely from subsurface gravel. Although Roth and Elachi<sup>10</sup> report that only a few particles exceeding the size criteria are needed to prevent detection of subsurface features, it is not clear what amount of gravel is critical. To assess the effect of gravel on these results, some corner reflectors have been buried at a shallow depth at Twentynine Palms; the covering soil consists of dry, sifted sand. A survey with a ground-based radar system is planned when circumstances permit.

The disturbed soil signals on the L-band imagery were strongest at low

angles of incidence. Since the ground surface was "radar rough", return from surfaces at or nearly normal to the incident beam would provide the maximum signal. If the slopes of the soil mounds parallel to the trenches were approximately 35 degrees with respect to the horizontal, these slopes would be roughly normal to the beam of the radar at an incidence angle of 35 degrees as shown in figure 7. This is likely because the angle of repose for granular particles is between 34 and 37 degrees. Signals similar to those noted on the imagery would thus be produced. This suggests that incidence angles equal to the natural angle of repose (i.e. 35 degrees) may be useful in radar systems attempting to identify disturbed soil signals.

Consideration has been given to the possibility that the signals from disturbed soil may result from a change in dielectric constant due to the lower density of the disturbed soil, coupled with the ability of the long-wavelength radar to penetrate and detect this change. Experiments are planned to resolve this issue.

Future work in the area of mine detection and extraction from synthetic aperture radar imagery should emphasize the application of various speckle-noise reduction techniques on the original imagery and also the signal processing of the original phase history information. Several speckle-noise reduction techniques are now available. However, for this effort, only one was used. This was a geometric filter that was applied twice to the original radar image in order to implement the pattern-finding algorithms. Analyzing

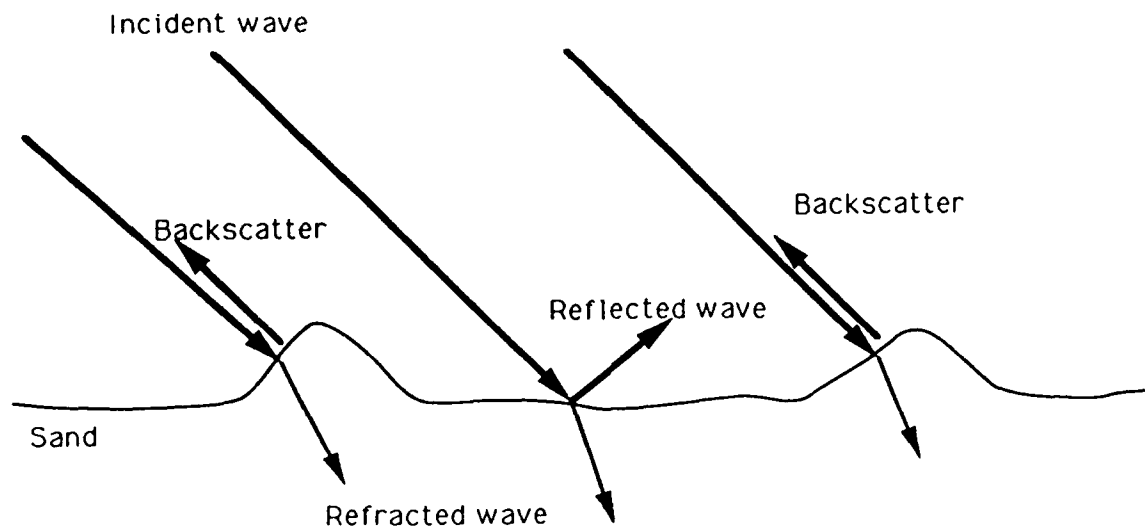


Figure 7 Backscatter Due to "Radar Rough" Surface

the signals in the phase histories deserves attention, as noted. When the signal-to-noise ratio is small as it is for buried mines, it would appear that this would be a good direction for further work.

Future work planned includes the use of systems such as wideband impulse

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radars and tomographic radars. Also, a calibrated ground-based system that can record signal return under varying conditions would be very useful in furthering the basic understanding of radar penetration of dry soil.

### Conclusions

The results of this project do not provide evidence that a long-wavelength synthetic aperture radar can be used to detect buried mines. However, it is possible that the lessons learned in terms of surface indicators and the progress made in developing pattern-finding algorithms could lead to more robust techniques for locating minefields. It is also likely that further signal processing efforts can contribute to finding minefields and possibly, the buried mines themselves.

Finally, it should be noted that military radar reconnaissance systems typically use short-wavelength radar to identify details of objects and terrain. Long-wavelength systems are not common in operational inventories, and if further research shows that disturbed soil resulting from military operations is preferentially detected by long-wavelength radar, then the addition of such systems to the operational inventory should be considered.

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